

Research Article

Biosecurity risks from weeds in crop seed lots imported into Canada: prevalence, trends, and herbicide resistance

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Abstract

The international crop seed trade is a major pathway for the unintentional introduction of non-native invasive plant species and herbicide-resistant weeds, posing biosecurity threats to agriculture and ecosystems. However, published studies examining weed contaminants in crop seed remain scarce. To address this, we analysed Canadian Food Inspection Agency (CFIA) monitoring data for 2,080 randomly sampled crop seed lots imported from the United States of America (USA) between 2007 and 2019. Both nations are major players in the global seed trade, making them key biosecurity case studies. We reported 262 contaminant species: 70% were introduced in Canada, 23% were native, and 7% had not been previously recorded (absent) in Canada. General weeds (not also imported as crops) comprised 63% of contaminant species; the remaining species were classified as seed of another crop. CFIA-classified noxious weeds (Classes 1–5) made up 12% of the contaminant species. Most contaminants were associated with only one or two crop species. There was a decline in general and noxious weeds, and noxious weeds were reported significantly less than non-noxious weeds over the study period. Entry-prohibited species (Class 1) were rare, limited to four records of *Cuscuta* spp. We identified 14 general weed species currently absent from Canada, notably the frequently reported *Trifolium vesiculosum*, along with *Galium parisiense*, *Torilis nodosa*, and *Trifolium hirtum*, all established in climatically similar regions of the USA, as well as *Bromus catharticus* and *Euphorbia aleppica*, identified as environmental and agricultural threats. Eight additional species, such as *Apera spica-venti*, currently limited to one Canadian province, pose a potential domestic spread risk. Reported Class 2 CFIA noxious weeds, including *Cirsium arvense*, *Convolvulus arvensis*, and *Elymus repens*, are of concern as their ecological range is not fully realised in Canada. *Chenopodium album* was the most widespread general weed detected across crop species. Contaminants with a known history of herbicide resistance in the USA but not in Canada increased significantly over time (e.g., *Sorghum halepense*, *Poa annua*), while those resistant in one Canadian province (*Bromus tectorum*) risk further spread in Canada. The introduction of new resistance is of concern when a contaminant species is reported in a crop type in Canada and documented as herbicide-resistant in the same crop type in the USA (*Poa annua* in forage and turf seed lots). Regulatory concerns include importing crops that are also classified as noxious or problematic weeds (*Bromus tectorum*, *Poa annua*), permitting contaminants absent from Canada in seed lots, and the dual classification of species that are native but also entry-prohibited (*Cuscuta campestris*). Our study highlights that expanded global seed trade necessitates ongoing seed lot monitoring, risk assessment, and adaptive regulations to help safeguard agriculture and biodiversity without hindering trade.



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Introduction

Canada plays a prominent role in the global seed trade as a leading producer, processor, and exporter of high-quality crop seed, engaging in trade with approximately two-thirds of countries worldwide (AAFC 2019; Seeds-Canada 2024). It is a primary supplier of seed for key crops such as canola, accounting for 22% of global canola seed production (USDA 2025). The seed industry makes a significant contribution to Canada's economy, generating approximately CAD \$6 billion annually in direct and indirect economic impacts (all subsequent monetary values are reported in CAD). It supports more than 63,000 jobs, provides \$2.26 billion in wages and salaries, and generates \$2.8 billion in seed sales to Canadian farmers (AAFC 2019).

Canada is globally ranked among the top five fastest-growing importers of seed for sowing, with the total value of imported seed exceeding the value of exported seed by 84% (OEC 2023; Statistics Canada 2025). A key contributor to this growth has been imports from the United States of America (USA), Canada's largest crop seed trade partner by both dollar value and tonnage (USDA 2024). Since 2019, Canada has imported an average of \$467 million in seed annually from the USA, representing 63% of the total value of seed imports from all trading partners. This accounts for 85% (137,468 tonnes) of the total volume of all seed imported annually into Canada (Seeds-Canada 2024). In 2023, the primary crop seeds imported from the USA into Canada were maize (corn) (55,170 tonnes), forage and grass seed (27,365 tonnes), pulses (16,926 tonnes), soybeans (14,279 tonnes), and canola (6,534 tonnes) (Seeds-Canada 2024). Additionally, the USA has the potential to export \$11.83 million more in crop seed to Canada than it currently does, highlighting opportunities to expand trade between the two countries (OEC 2023), a potential that will require continued cross-border cooperation and regulatory alignment. At the same time, the growth of Canada's seed import market increases the risk of weed incursions via contaminants in crop seed lots, underscoring the need for robust biosecurity measures.

The rate of new plant species introductions in Canada has grown exponentially in recent decades with the expansion of global trade and travel (ECCC 2017). An estimated 58% of invasive plant species in Canada resulted from deliberate introductions, including agronomic crops, landscape plants, ornamentals, and medicinal plants (CFIA and McClay 2008). The remaining plant introductions occurred unintentionally, primarily as contaminants in imported agricultural seed lots, grain and cereal imports, soil, machinery, vehicles, or as stowaways on cargo and passenger ships (ECCC 2017).

Agricultural seed lots have historically been a significant pathway for unintentional introductions of naturalised weeds around the world (Mack and Lonsdale 2001), particularly when these weeds are introduced into regions with climates similar to those where they are already established (Hulme 2024). The international crop seed trade continues to serve as a significant introductory pathway for weed seeds, making it a critical concern for biosecurity management (Buddenhagen et al. 2021). Effective management of these pathways requires understanding the mechanisms of introduction and spread of invasive species, as well as their economic and ecological consequences (Seebens et al. 2022).

The introduction of non-native plant species through pathways such as agricultural seed lot imports has intensified the ongoing challenges of weed management

in Canada, resulting in substantial economic, environmental, and health impacts (CFIA 2011). Managing weeds in Canadian pastures and crops costs an estimated \$2.2 billion annually, equivalent to roughly 15% of the total value of annual plant products (CFIA and McClay 2008). Of this amount, growers bear between \$1.1 and \$1.5 billion annually in costs due to increased herbicide use and reduced crop yield and quality (Beckie 2024).

Effective weed management is critical for reducing these costs and maintaining high crop yields. Without intervention, combined estimates for Canada and the USA suggest weed interference could reduce maize yields by 50%, valued at \$36.1 billion annually (Soltani et al. 2016), and soybean yields by 52%, valued at \$23.2 billion annually (Soltani et al. 2017). Wheat is also significantly affected, with potential yield losses of 24% in winter wheat, valued at approximately \$3 billion annually, and 20% in spring wheat, valued at \$1.9 billion annually (Flessner et al. 2021). In Canada, effective weed management has a greater impact on canola yields than fertiliser or genetics, with weed interference alone causing an estimated average yield loss of 30% (Blackshaw et al. 2011; Geddes et al. 2022). Recent increases in herbicide resistance are further increasing weed control costs, reducing management effectiveness, and potentially leading to greater yield losses (Flessner et al. 2021). Nevertheless, in Canada, herbicide-based weed control can still yield a return of approximately three dollars for every dollar invested (Stephenson 2003).

Herbicide-resistant (HR) biotypes represent a significant and growing challenge in Canada, which ranks third globally for countries with the highest number of HR weeds, with 56 documented biotypes (Heap 2025). Among the most problematic are *Avena fatua*, *Conyza canadensis*, and *Kochia scoparia*, which exhibit resistance to commonly used herbicide groups, including EPSP synthase inhibitors (those containing glyphosate), acetolactate synthase inhibitors, and acetyl-CoA carboxylase inhibitors (Beckie 2018; Heap and Duke 2018). The five most frequently reported HR weeds in Canada, in order of occurrence, are *Avena fatua*, *Amaranthus retroflexus*, *Setaria viridis*, *Kochia scoparia*, and *Amaranthus powellii* (Heap 2025). The challenge posed by HR weeds is particularly acute in Western Canada, the country's main region for crop production, where nearly 54% of cropland is affected (Beckie 2018). Key crops, such as barley, are especially impacted by the growing number of resistant weed species in Canada (Hulme 2022). In Saskatchewan (Central Canada), annual losses from herbicide resistance are estimated at \$343 million, due to lower yields and quality, as well as higher weed control costs (Geddes et al. 2024). In response, many farmers are shifting from reactive herbicide use to prevention-focused strategies aimed at stopping weed seeds from entering the soil in the first place (Beckie et al. 2019). This proactive approach requires maintaining high analytical purity in crop seed lots and preventing the establishment of new herbicide-resistant biotypes. The escalating prevalence of HR weeds in Canada highlights the need for more sustainable and innovative management strategies to protect both agricultural productivity and ecosystem health.

In addition to herbicide resistance, understanding whether a plant species is native, already present as an introduced species, or absent from a country is important for effective weed management. These classifications inform regulatory priorities, guide control strategies, and support early detection and response (Pyšek et al. 2004). Of the estimated 5,124 vascular plant species growing in Canada,

approximately 25% (1,295 species) are introduced, with the remainder considered native (Desmet and Brouillet 2013). Among the introduced species, 486 are classified as invasive due to their impacts on biodiversity, ecosystem functioning, agricultural productivity, trade, and human health (CFIA and McClay 2008). Distinguishing invasive plant species from other introduced plants presents a significant regulatory challenge (Hulme 2006). However, accurately assessing and prioritising these species is essential to reduce their harmful impacts, but doing so requires comprehensive data and coordination across multiple stakeholders, which can be both logistically and financially demanding. Species classified as absent, meaning not currently known to occur in the country, are of particular concern, especially when detected as contaminants in crop seed lots. Their presence may signal a new introduction pathway for invasive species and could lead to ecological or economic consequences if they become established.

To mitigate the risks posed by weeds, Canada has implemented measures to limit the introduction and spread of invasive weed species, particularly via agricultural seed lot contamination. The Canadian Food Inspection Agency (CFIA) enforces these regulations, with the Weed Seeds Order (WSO) of the Seeds Act being the cornerstone of this risk reduction framework. The WSO aims to prevent the introduction of new weed species and limit the presence of weed seeds in crop seed sold or imported into Canada (CFIA 2016b). Although updates to the WSO have been infrequent (most recently in 2016), each revision is intended to reflect changes in weed distribution, advances in management practices, and emerging or changing risks from seed imports. The WSO applies to seeds used in agriculture, residential products such as wildflower mixtures, and land reclamation (CFIA 2016b). By regulating weed seeds across these applications, the WSO plays a critical role in protecting agricultural productivity and preserving natural ecosystems.

In addition to the WSO, Canada employs other regulatory measures to mitigate weed seed risks and ensure compliance with international trade standards. These include the enforcement of the Plant Protection Act, which prohibits the importation of crop seed if it is classified as, or contains, a pest plant (CFIA 2019). Canada also requires import permits, phytosanitary certificates, and treatment documentation to verify that imported seed lots meet the country's biosecurity standards (CFIA 2016a). The CFIA monitors seed lots for compliance with national regulations by sampling and testing seed lots for weed seed contamination. In addition to government oversight, there are additional purity standards requiring that seed lots remain below specific thresholds for weed seed content and be free of noxious weeds to qualify as certified seed under the OECD seed scheme (Buddenhagen et al. 2022).

Together, all these processes play a critical role in preventing the introduction of invasive non-native plant species, safeguarding agricultural productivity, and maintaining Canada's biosecurity. Non-compliance can impose significant costs, as contaminated seed lots may require re-cleaning, re-exporting, or destruction (Wilson et al. 2016; USDA 2019; Buddenhagen et al. 2022). Collaboration with international regulatory bodies and the implementation of public awareness initiatives are also essential for strengthening biosecurity systems and addressing the risks posed by global seed trade. In an increasingly interconnected world, effective and coordinated management of the crop seed trade pathway is essential to reduce the risk of future plant invasions (Hulme 2009).

Study aims

To evaluate the role of international crop seed trade as a pathway for the unintentional introduction and spread of non-native invasive, previously unrecorded, and herbicide-resistant weed species in Canada, we analysed a unique dataset of official Canadian crop seed lot inspections to address the following research questions:

1. How frequently are CFIA-classified noxious weeds, general weeds (not also imported as crop seed), species not currently known to be present in Canada, and emerging herbicide-resistant weeds reported in imported seed lots, and do any of these categories show significant trends over time?
2. Are most contaminant weeds associated with only a few crop species, or do some occur across a broad range of crops?
3. Which contaminant species may pose the greatest risk of establishing or spreading, including the introduction of new herbicide-resistant weeds into Canada?
4. How do current CFIA regulatory classifications and frameworks align with the potential risks associated with these contaminant species?

Methods

Seed lot inspection data

This study used official inspection data for crop seed lots imported into Canada from the USA between 2007 and 2019, provided by the CFIA Seed Section (Ottawa). Monitoring samples were collected by CFIA seed inspectors, and the seed lots were analysed with accompanying data compiled by the CFIA Seed Science and Technology Section (Saskatoon), which operates an International Seed Testing Association (ISTA) and ISO 17025-accredited laboratory. Canada monitors imports from all countries, but given that the USA is its largest trading partner for crop seeds (Seeds-Canada 2024), our analysis focused exclusively on these imports. During this period, the CFIA monitored 2,080 randomly selected crop seed lots from the USA to ensure compliance with Canadian seed standards. While all sampling data were provided to us, these random samples represented only a small fraction of the total seed lots imported annually from the USA into Canada, and information on the total number of imported lots was not provided to us.

Seed lot inspection records included the following information relevant for our analysis: imported crop species, contaminant species detected, and sampling year. Because a single seed lot can have multiple contaminants from different taxa, a contaminant record refers to any time a single contaminant taxon was reported in a single seed lot. Contaminants were identified at the species level in 70% of cases, with 27% identified at the genus level and 3% at the family level. Reporting at the genus and family level is not uncommon in official inspection data (Rubenstein et al. 2021), particularly when contaminants within the same genus are morphologically challenging to distinguish (James et al. 2014). Because the number of seeds for each contaminant found in a seed lot was not provided to us, we only considered the presence or absence of a contaminant species, rather than its abundance (Rubenstein et al. 2023).

Data preparation

Plant names were standardised using the most recent (2025) taxonomy listed in the Database of Vascular Plants of Canada (VASCAN) (Desmet and Brouillet 2013) (<https://data.canadensys.net>). Additionally, VASCAN was used to classify contaminants based on their origin status in Canada, identifying species as either introduced, native, or absent (Desmet and Brouillet 2013). Absent species were defined as plants that have not been reported as occurring in the wild within Canada (Desmet and Brouillet 2013). A species was classified as introduced or native for the entire country if it held either status in at least one Canadian province. In cases where a species was listed as native in one province and introduced in another (e.g., native in Ontario but introduced in British Columbia), it was classified as native by default. Species listed in VASCAN as excluded or extirpated, or not listed at all, were categorised as absent. Additional details on these classifications can be found in the VASCAN database: <https://data.canadensys.net/vascan/about>.

Contaminant species were also classified as either a ‘general weed’ or ‘seed of another crop’. A species was considered seed of another crop if it was a declared crop in another instance within the CFIA import dataset itself or if it appeared as a crop species in official CFIA documentation, including the “Canadian Methods and Procedures for Testing Seed” (CFIA 2024a), the ‘Approximate Number of Seeds per Gram’ section of “The ABCs of Seed Importation into Canada” (CFIA 2022), or the “List of Grains and Field Crops” (CFIA 2015). Any contaminant species not meeting these criteria was categorised as a general weed.

Finally, contaminant species were categorised according to their official CFIA noxious weed classification from the WSO, ranging from Class 1 to 5 for noxious weeds and Class 6 for all other contaminants (CFIA 2016b). While Class 1 – Prohibited Noxious Weed Seeds has a zero-tolerance policy, permissible limits for the remaining classes (including Class 6) vary depending on the crop type and intended use. These limits are outlined in Schedule I of the “Seeds Regulations” (C.R.C., c. 1400), which specifies the maximum allowable quantities of weed seeds in different seed classes (CFIA 2025a). Descriptions of each CFIA weed seed class are presented in Table 1 (CFIA 2009, 2011, 2016b, 2025a).

Additionally, species were classified as invasive if they were referenced in the “Invasive Alien Plants in Canada” technical report by CFIA and McClay Ecoscience (CFIA and McClay 2008). The full list of 486 invasive species referenced in the report was provided to our study by CFIA.

The International Herbicide-Resistant Weed Database (<https://www.weed-science.org>) was used to identify contaminant species that have historically evolved herbicide resistance in weedy contexts in Canada and the USA (Heap 2025). However, when the contaminant was a seed of another crop, the species was not categorised as herbicide-resistant. For example, although herbicide-resistant varieties of *Zea mays* (maize) are widely cultivated, they have not been documented as herbicide-resistant weeds in either country and were therefore excluded from the analysis. In contrast, crop species such as *Lolium multiflorum*, which also appeared as contaminants in this dataset, were included because they have been recorded as herbicide-resistant weeds in both Canada and the USA.

Table 1. CFIA noxious weed seed classes and their corresponding category descriptions.

CFIA class	Noxious weed seed category	Class description	Composition
Class 1	Prohibited noxious	Includes some species not yet present in Canada (absent), as well as species under official control due to incomplete ecological range expansion. Control efforts focus on eradication or containment. These species are strictly prohibited in all imported and domestic seed lots due to their potential economic, environmental, and health risks.	25 species, 1 genus (<i>Cuscuta</i> spp.)
Class 2	Primary noxious	Species present in Canada but not yet at their full ecological range. These weeds are not under official control but can reduce seed value, interfere with agricultural production, and pose risks to economic and human health.	36 species
Class 3	Secondary noxious	Relatively common and widespread across Canada. These weeds lower seed value or disrupt agricultural uses but are generally easier to manage in cultivated fields compared to more restrictive classes.	29 species, 1 genus (<i>Rumex</i> spp.)
Class 4	Secondary noxious	Relatively common and widespread across Canada. These weeds lower seed value or disrupt agricultural uses but are generally easier to manage in cultivated fields compared to more restrictive classes.	2 species, 3 genera
Class 5	Noxious	Includes species from Class 4 along with two additional species. Common across Canada, they can reduce seed value or interfere with agricultural use. The key distinction between Class 4 and Class 5 lies in the type of seed mixture in which they are found: Class 4 species occur in turfgrass seed lots, whereas Class 5 species are found in lawn or ground cover mixtures.	4 species, 3 genera
Class 6	Other (non-noxious)	This class includes widespread species in Canada that may warrant monitoring to maintain seed quality and prevent spread into new provinces, as well as absent species, some of which have not been formally assessed but may require biosecurity attention.	All others

Statistical analysis

We analysed thirteen consecutive years of seed lot sampling data (2007–2019), averaging 160 inspections per year, for a total of 2,080 seed lots imported from the USA. Given that 70% of contaminant records were identified at the species level, the analysis was conducted at this taxonomic level. Genus- and family-level records were excluded from all analyses, except in Table 2, which lists Class 1 – Prohibited Noxious Weed Seeds. Due to the high regulatory concern associated with entry-prohibited weeds, all relevant records were retained in this table regardless of their level of taxonomic resolution.

The annual percentage of contaminant species in each category (e.g., native, introduced, noxious) was calculated as the number of species in the category divided by the total number of contaminant species recorded for that year.

A non-parametric Mann–Kendall test was used to evaluate if there was a significant upward or downward temporal trend in the prevalence of contaminant species categorised by origin status (absent, introduced, or native), noxious weed status (Classes 1 to 5), general weeds, and species with a history of herbicide resistance. This method is well-suited for analysing non-parametric data and detecting monotonic trends in time series without requiring assumptions of normality (Yue et al. 2002).

Additionally, a Wilcoxon signed-rank test was used to compare the reporting frequency of non-native species introduced into Canada with that of native species and species absent from Canada, the prevalence of Class 1 to 5 noxious weeds with Class 6 species, and general weeds with contaminants classified as seed of another crop (Wilcoxon et al. 1970). A Spearman’s rank correlation was performed to evaluate the relationship between the number of contaminated seed lots and the total number of inspected seed lots for the top 20 most frequently inspected crops, representing 83% of the dataset. This method was selected for its robustness to outliers and its suitability for non-linear relationships, without assuming normality (Hauke and Kossowski 2011). All figures were generated using Python with the Matplotlib and Pandas libraries (Hunter 2007; McKinney 2010).

Results

Between 2007 and 2019, Canada monitored 113 crop species and seven seed mixtures imported from the USA. The 20 most frequently inspected species (Table 2) made up 83% of all inspections and were primarily arable, forage, and turf crops. The crops with the highest proportion of seed lots containing contaminants were *Trifolium repens* (white clover) at nearly 93%, *Dactylis glomerata* (orchard grass) at 89%, and lawn seed mixtures at 88%. However, these contamination rates should be interpreted with caution, as they do not reflect the noxious weed classification or origin status of the contaminants, which are addressed in subsequent sections. Additionally, there was no significant correlation between the number of seed lots inspected within each crop and the corresponding proportion found to be contaminated (Spearman’s correlation, $p = 0.560$). For instance, *Zea mays*, the most frequently inspected crop, had the lowest contamination rate, at less than 2%.

Table 2. Top 20 most inspected crop species for seed lots imported from the USA. Species are listed in descending order by frequency of inspection ranking.

Crop	Frequency of inspection ranking	Primary crop types(s)	Percentage of seed lots contaminated
<i>Zea mays</i>	1	Arable	1.7
<i>Poa pratensis</i>	2	Forage, turf	53.8
<i>Phaseolus vulgaris</i>	3	Arable	2.3
<i>Lolium perenne</i>	4	Forage, turf	59.1
<i>Pisum sativum</i>	5	Arable	3.1
<i>Lolium multiflorum</i>	6	Forage	63.3
<i>Brassica napus</i>	7	Arable	6.5
<i>Medicago sativa</i>	8	Forage	42.1
<i>Trifolium pratense</i>	9	Forage	74.3
<i>Glycine max</i>	10	Arable	3.0
<i>Lolium arundinaceum</i> (<i>Festuca arundinacea</i>)	11	Forage, turf	75.0
<i>Dactylis glomerata</i>	12	Forage	89.1
<i>Raphanus sativus</i>	13	Forage, vegetable	35.8
<i>Festuca rubra</i>	14	Forage, turf	53.2
<i>Trifolium repens</i>	15	Forage	92.9
<i>Sorghum</i> × <i>drummondii</i>	16	Forage	11.1
<i>Festuca brevipila</i>	17	Forage, turf	44.0
<i>Echinochloa esculenta</i>	18	Forage	77.3
<i>Trifolium incarnatum</i>	19	Forage	60.0
Lawn mixture	20	Turf	88.2

Overview of contaminant species

A total of 262 contaminant species were reported across all officially monitored seed lots from the USA (Suppl. material 1: table S1). Of these, the majority (166 species, 63%) were classified as general weeds that are not also imported as crops into Canada (Fig. 1). The remaining contaminant species were considered seed of another crop. Based on their origin status within Canada, 182 species (70%) were classified as introduced, 61 species (23%) as native, and 19 species (7%) as absent, indicating they are not currently present in Canada (Fig. 1). Regarding

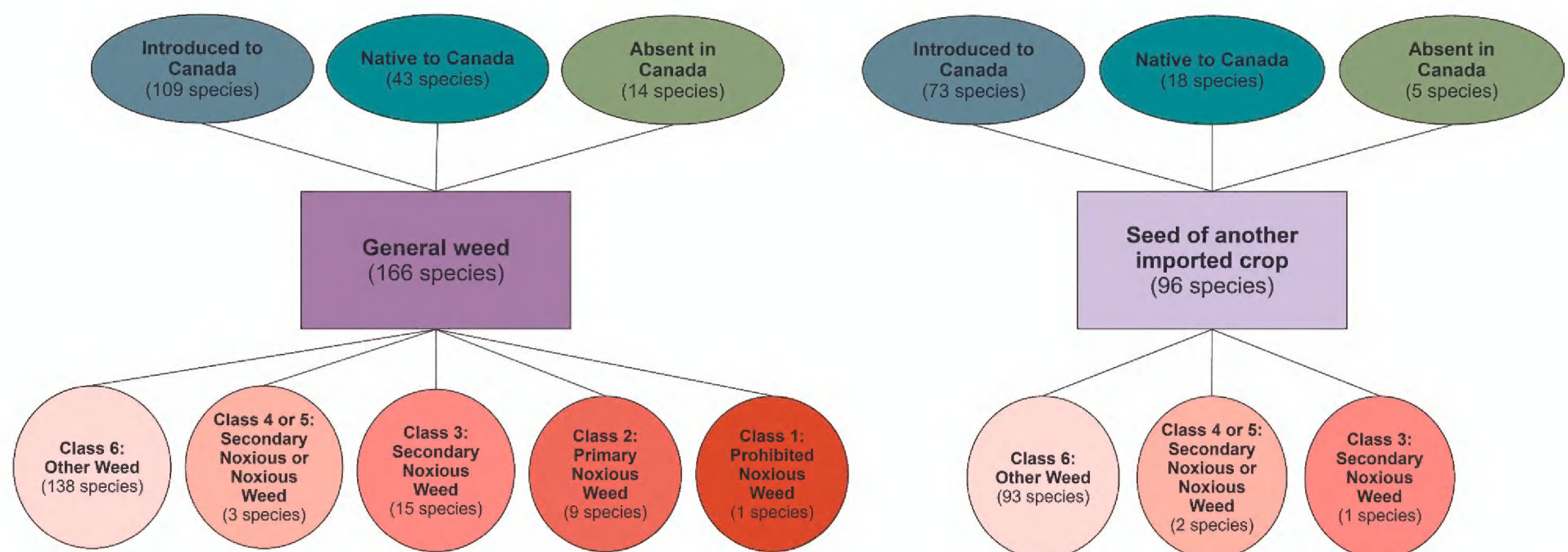


Figure 1. Classification of contaminant species by contaminant type (general weed or seed of another imported crop), origin status (introduced, native, or absent in Canada), and CFIA noxious weed classification (Class 1 to 5 or Class 6). All species, regardless of origin status, were also assigned to one of the six CFIA weed classes.

CFIA noxious weed classifications, 31 species (12%) were assigned to Classes 1 through 5 (noxious), while the remaining 231 species (88%) were classified as Class 6 (non-noxious) (Fig. 1). The latter category includes contaminants that are either already widespread in Canada or are absent, some of which have not yet been formally evaluated for noxious designation. Additionally, 126 species (48%) were listed as invasive (Suppl. material 1: table S1) according to the “Invasive Alien Plants in Canada” technical report (CFIA and McClay 2008).

Trends related to general weeds and CFIA noxious weeds

Fig. 2 presents temporal trends for general weeds (species not also imported as crop seeds) and CFIA-classified noxious weeds (Classes 1 to 5). General weeds showed a significant decrease over time (Mann–Kendall, $\text{Tau} = -0.590$, $p = 0.004$). A decreasing trend was also observed for CFIA-classified noxious weeds ($\text{Tau} = -0.333$), but it was not statistically significant ($p = 0.129$). Class 1 to 5 noxious weeds were reported significantly less often than Class 6 species, occurring at 69% lower frequency on average (Wilcoxon signed-rank test, $p = 0.0002$). In contrast, general weeds and contaminants classified as seed of another crop were reported at similar rates, with no significant difference between the two groups ($p = 0.414$). Fig. 2 shows the annual percentage of reported general weeds and CFIA-classified noxious weeds (Classes 1 to 5), with the remaining proportion each year representing other categories (Class 6 and seed of another crop), summing to 100%.

Throughout the study period, detections of prohibited noxious weeds (Class 1) were rare, with only four reports (Table 3): one seed lot containing *Cuscuta campestris* and three more with *Cuscuta* spp. (identified only to genus level). Two of these reports were found in seed lots of *Rudbeckia hirta* (black-eyed Susan), a widely cultivated ornamental flower species in Canada, and the other two in *Trifolium pratense* (red clover). Primary noxious weeds (Class 2) were somewhat more common, comprising nine species (3% of all contaminants) across 36 seed lots (Table 3). The most frequently reported of this class were *Cirsium arvense* (9 seed lots), *Elymus repens* (9), and *Convolvulus arvensis* (7). All Class 1 and 2 species were introduced, apart from *Cuscuta campestris*, which is native. The crop species most frequently associated with these noxious weeds were *Lolium perenne* (perennial

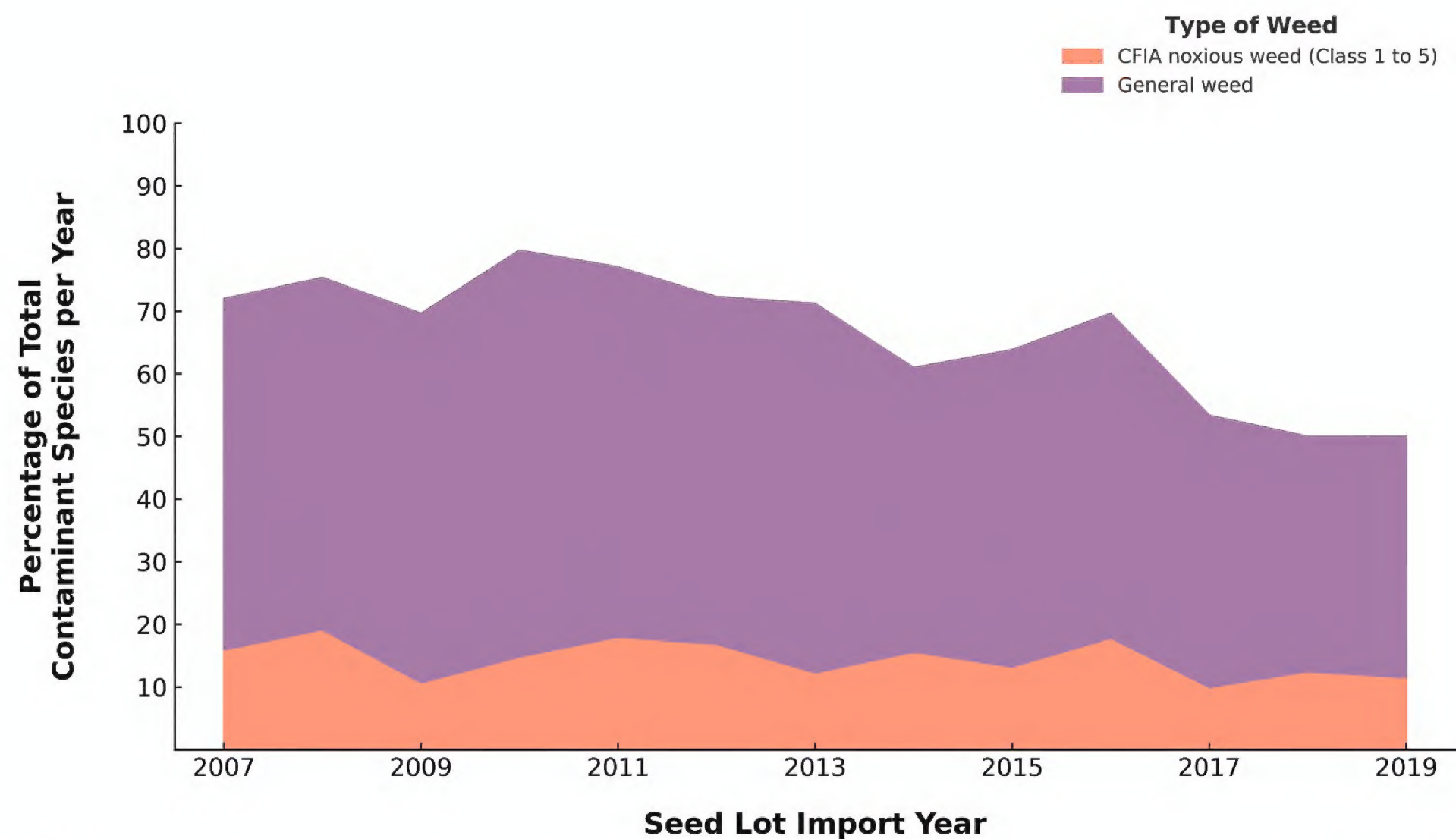


Figure 2. Temporal trends in contaminant species reported in seed lots imported from the USA, showing the annual proportion of general weeds and CFIA-classified noxious weeds (Classes 1 to 5).

Table 3. CFIA-prohibited (Class 1) and primary (Class 2) noxious weeds reported in imported seed lots. Species are listed in descending order based on the total number of seed lots in which they were reported.

Contaminant species (synonym)	CFIA noxious weed classification	Origin status in Canada	Crops reported with contaminant (number of seed lots)
<i>Cirsium arvense</i>	Primary (Class 2)	Introduced	<i>Lolium perenne</i> (6), <i>Bouteloua gracilis</i> (1), <i>Elymus canadensis</i> (1), <i>Festuca rubra</i> (1)
<i>Elymus repens</i> (<i>Elytrigia repens</i>)	Primary (Class 2)	Introduced	<i>Lolium perenne</i> (4), <i>Lolium multiflorum</i> (2), <i>Alopecurus arundinaceus</i> (1), <i>Bromus inermis</i> (1), <i>Dactylis glomerata</i> (1)
<i>Convolvulus arvensis</i>	Primary (Class 2)	Introduced	<i>Raphanus sativus</i> (3), <i>Echinochloa frumentacea</i> (1), <i>Fagopyrum esculentum</i> (1), ground cover mixture (1), <i>Poaceae</i> sp. (1)
<i>Cuscuta</i> sp.	Prohibited (Class 1)	Introduced	<i>Trifolium pratense</i> (2), <i>Rudbeckia hirta</i> (1)
<i>Raphanus raphanistrum</i>	Primary (Class 2)	Introduced	<i>Fagopyrum esculentum</i> (1), <i>Trifolium pratense</i> (1), <i>Vicia sativa</i> (1)
<i>Setaria faberi</i>	Primary (Class 2)	Introduced	<i>Panicum virgatum</i> (3)
<i>Conium maculatum</i>	Primary (Class 2)	Introduced	<i>Trifolium pratense</i> (2)
<i>Cuscuta campestris</i>	Prohibited (Class 1)	Native	<i>Rudbeckia hirta</i> (1)
<i>Jacobaea vulgaris</i> (<i>Senecio jacobaea</i>)	Primary (Class 2)	Introduced	<i>Festuca rubra</i> (1)
<i>Lepidium draba</i>	Primary (Class 2)	Introduced	<i>Alopecurus arundinaceus</i> (1)
<i>Sorghum halepense</i>	Primary (Class 2)	Introduced	<i>Sorghum</i> × <i>drummondii</i> (1)

ryegrass), with Class 2 species found in 10 seed lots; *Trifolium pratense* (red clover), with Class 1 and Class 2 species found in 5 seed lots; and *Panicum virgatum* (switchgrass) and *Raphanus sativus* (radish), each found in 3 seed lots (Table 3).

Secondary noxious weeds (Class 3) were the most frequently reported noxious weed category, comprising 16 species (6% of all contaminants) found in 103 seed lots. In contrast, Classes 4 and 5 together accounted for only five species (2%) across 19 seed lots. A full list of these species is provided in Suppl. material 1: table S1. Notably, several species in these classes were also imported as the declared

crop seed in other seed lots, including *Bromus tectorum* (Class 3) and *Panicum miliaceum* and *Panicum virgatum*, which were assigned to Class 4 or 5 depending on the crop type. Some of these noxious weeds are native to Canada, such as *Ambrosia artemisiifolia* and *Galium aparine* (both Class 3), as well as *Panicum capillare* and *Panicum virgatum* (Class 4 or 5).

Trends related to the origin status of contaminant species

Annual trends in contaminant species are shown (Fig. 3). These were categorised as absent, introduced, or native to Canada. Mann–Kendall trend analysis did not reveal any significant increases or decreases in the reporting of these categories over the study period. On average, about 3% of contaminant species reported each year were classified as absent from Canada. Introduced species, however, were detected significantly more often than native or absent species, as indicated by a Wilcoxon signed-rank test ($p = 0.0002$). On average, introduced species were reported 56% more frequently than native species and 74% more frequently than absent species. These patterns are visually represented in Fig. 3.

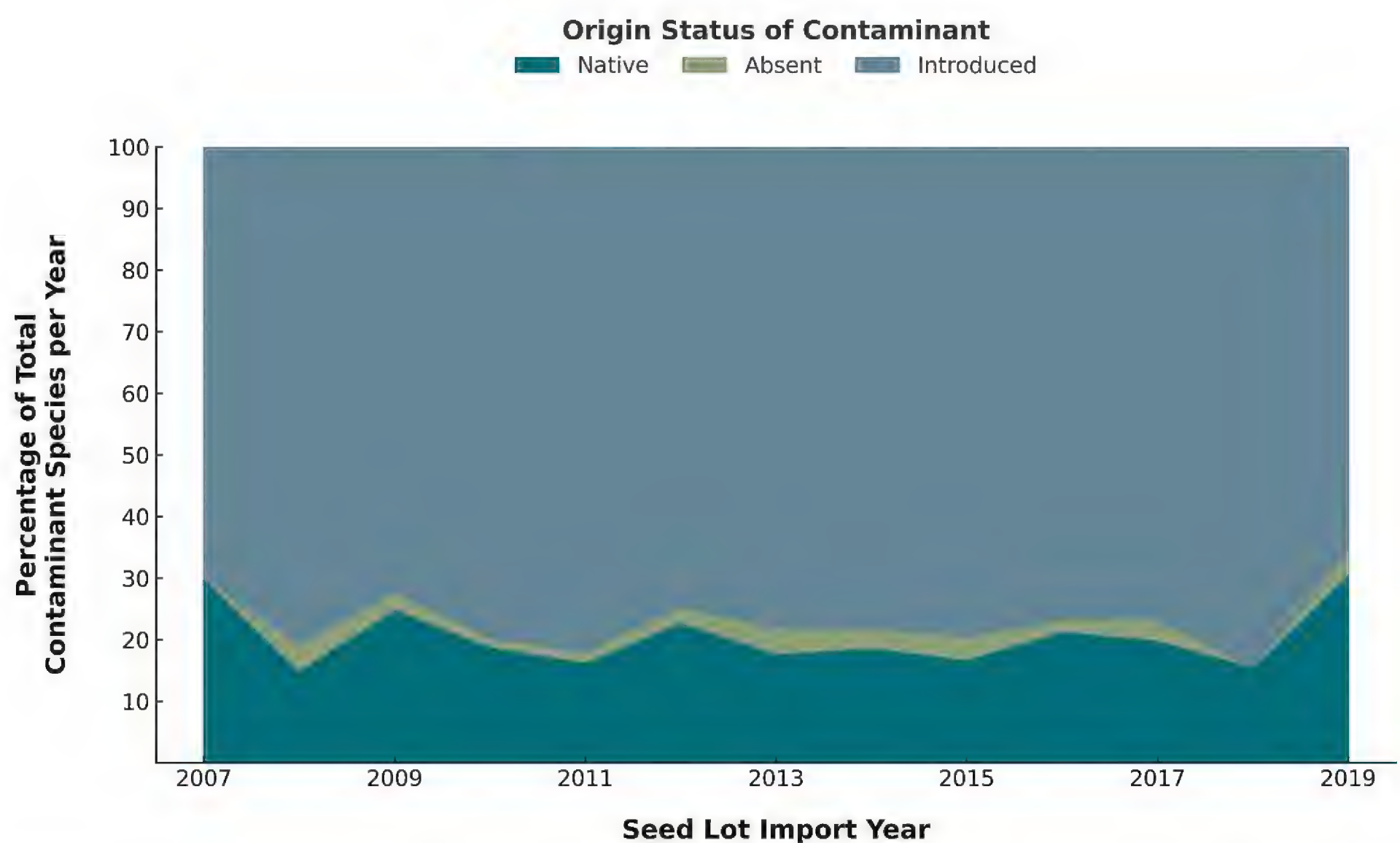


Figure 3. Temporal trends in contaminant species in imported seed lots, illustrating the annual distribution of native, introduced, and absent species.

Among the 19 contaminant species not currently known to be present or established in Canada, 14 are classified as general weeds (species not also imported as crop seeds) (Table 4). All 14 species were categorised as Class 6, which permits their presence in seed lots provided they remain below the allowable threshold for the corresponding seed grade and crop in which they were reported. The most frequently reported absent species was *Trifolium vesiculosum*, which appeared in four seed lots of *Trifolium* crop species over the study period. The remaining five

absent contaminant species were *Campeiestachys dahurica* (syn. *Elymus dahuricus*), *Eragrostis tef*, *Phaseolus vulgaris*, *Vigna angularis*, and *Vigna radiata*, all of which are seed of another crop, as they are cultivated in Canada. While these species are grown agriculturally, they are not known to be established in the wild. In addition to the absent species, eight other general weed species were classified as introduced in only one Canadian province (Table 4). The most frequently reported among them was *Apera spica-venti*, found in 28 seed lots of *Poa pratensis* (Kentucky bluegrass), two of *Poa trivialis*, and one of *Agrostis gigantea*.

Table 4. General weed species that are absent from Canada or introduced in only one province, along with the crop species in which they were reported. Species are listed in descending order by the number of seed lots in which they appeared.

Contaminant species (synonym)	Origin status in Canada	Crops reported with contaminant (number of seed lots)
<i>Apera spica-venti</i>	Introduced in 1 province	<i>Poa pratensis</i> (28), <i>Poa trivialis</i> (2), <i>Agrostis gigantea</i> (1)
<i>Trifolium vesiculosum</i>	Absent	<i>Trifolium pratense</i> (3), <i>Trifolium repens</i> (1)
<i>Bromus catharticus</i>	Absent	<i>Lolium arundinaceum</i> (1), wildflower mixture (1)
<i>Holcus mollis</i>	Introduced in 1 province	<i>Poa pratensis</i> (1), <i>Agrostis capillaris</i> (1)
<i>Lythrum portula</i>	Introduced in 1 province	<i>Lolium</i> sp. (1), <i>Agrostis capillaris</i> (1)
<i>Torilis nodosa</i>	Absent	<i>Cichorium intybus</i> (1), <i>Dactylis glomerata</i> (1)
<i>Aristolochia littoralis</i> (<i>Aristolochia elegans</i>)	Absent	<i>Agrostis</i> sp. (1)
<i>Euphorbia aleppica</i>	Absent	Wildflower mixture (1)
<i>Gaillardia megapotamica</i>	Absent	Wildflower mixture (1)
<i>Galium parisiense</i>	Absent	<i>Agrostis capillaris</i> (1)
<i>Galium tricornerutum</i>	Introduced in 1 province	<i>Vicia villosa</i> (1)
<i>Indigofera hirsuta</i>	Absent	<i>Vigna unguiculata</i> (1)
<i>Linum grandiflorum</i>	Absent	Wildflower mixture (1)
<i>Paspalum conjugatum</i>	Absent	<i>Echinochloa esculenta</i> (1)
<i>Plantago virginica</i>	Introduced in 1 province	<i>Poa pratensis</i> (1)
<i>Polygonum plebeium</i>	Absent	<i>Phacelia tanacetifolia</i> (1)
<i>Sida spinosa</i>	Introduced in 1 province	<i>Echinochloa esculenta</i> (1)
<i>Sorghum halepense</i>	Introduced in 1 province	<i>Sorghum</i> × <i>drummondii</i> (1)
<i>Trifolium hirtum</i>	Absent	<i>Trifolium pratense</i> (1)
<i>Trifolium reflexum</i>	Absent	<i>Panicum virgatum</i> (1)
<i>Urochloa ramosa</i>	Absent	<i>Echinochloa esculenta</i> (1)
<i>Veronica agrestis</i>	Introduced in 1 province	<i>Lolium multiflorum</i> (1)

Distribution of contaminants across multiple crop species

Although individual species could appear as contaminants in multiple crops, a considerable proportion of contaminants (120 species, 46%) were found in only a single crop species (Fig. 4). Contaminant species classified as absent in Canada were found in either one or two crop species, with a median occurrence in one crop. Native species contaminated between one and 29 crop species, also with a median of one crop. Introduced species contaminated between one and 22 crop species, with a median of two crop species. These medians indicate that most contaminant species are associated with only one or two crop species.

Among the contaminants found in the greatest number of crop species (≥10), *Poa pratensis* was the most frequently identified, occurring in 29 crop species, followed by *Chenopodium album*, reported in 22 crop species (Table 5). However, since

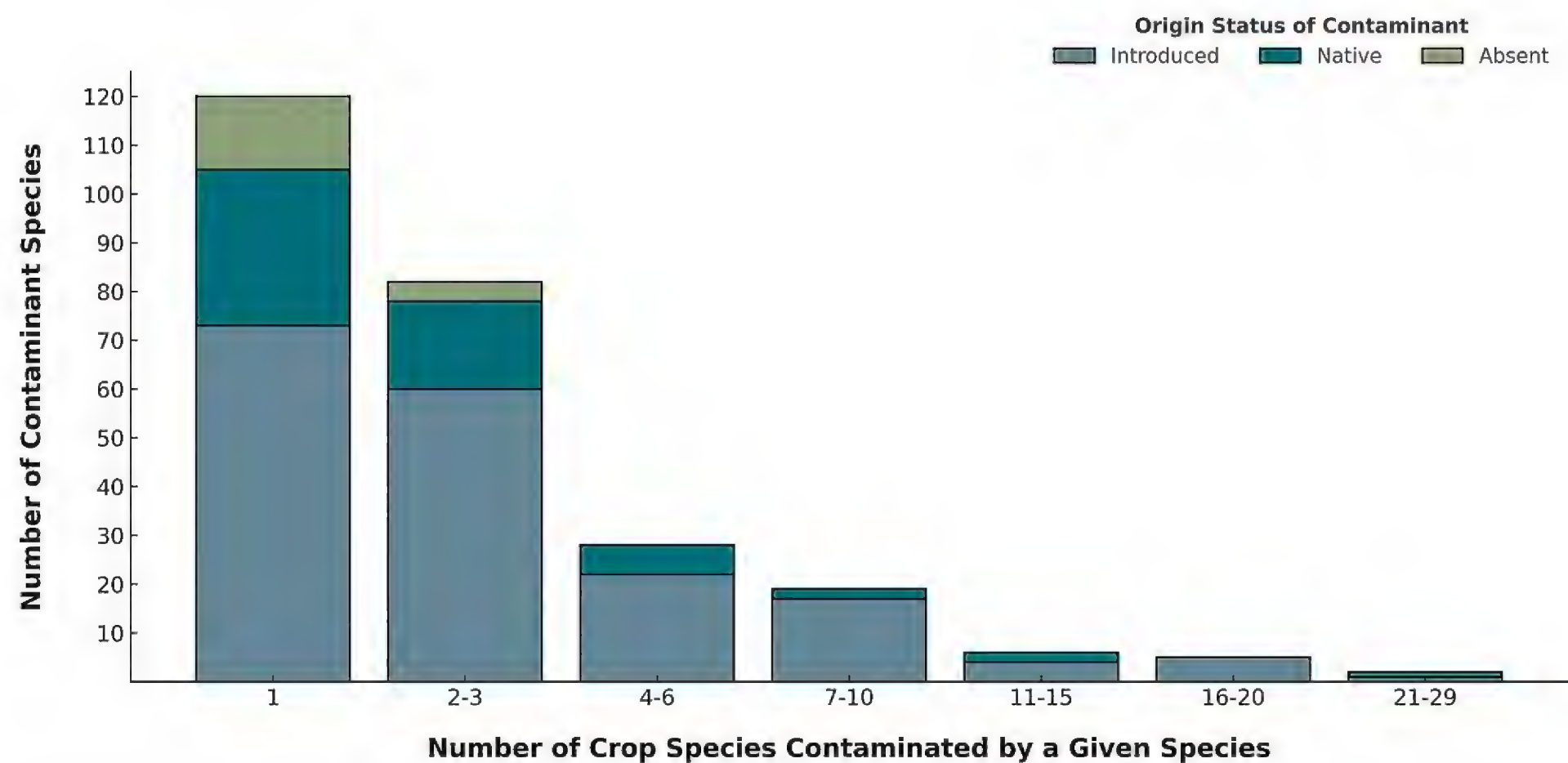


Figure 4. Number of crop species in which each contaminant species was reported, grouped by origin status in Canada (introduced, native, or absent).

Table 5. Contaminant species reported in ten or more crop species. Species are listed in descending order by the number of crop species in which they were reported.

Contaminant species (synonym)	Number of crop species contaminated	Origin status in Canada	Classified as general weed	CFIA noxious weed classification
<i>Poa pratensis</i>	29	Native	N	Other (Class 6)
<i>Chenopodium album</i>	22	Introduced	Y	Other (Class 6)
<i>Phleum pratense</i>	20	Introduced	N	Other (Class 6)
<i>Triticum aestivum</i>	19	Introduced	N	Other (Class 6)
<i>Medicago sativa</i>	18	Introduced	N	Other (Class 6)
<i>Echinochloa crus-galli</i>	17	Introduced	Y	Other (Class 6)
<i>Trifolium pratense</i>	17	Introduced	N	Other (Class 6)
<i>Trifolium hybridum</i>	15	Introduced	N	Other (Class 6)
<i>Bromus tectorum</i>	13	Introduced	N	Secondary (Class 3)
<i>Festuca rubra</i>	13	Native	N	Other (Class 6)
<i>Poa annua</i>	13	Introduced	N	Other (Class 6)
<i>Vulpia myuros</i>	12	Introduced	Y	Other (Class 6)
<i>Galium aparine</i>	11	Native	Y	Secondary (Class 3)
<i>Lolium pratense</i> (<i>Festuca pratensis</i>)	11	Introduced	N	Other (Class 6)
<i>Brassica napus</i>	10	Introduced	N	Other (Class 6)
<i>Elymus trachycaulus</i>	10	Native	N	Other (Class 6)
<i>Setaria viridis</i>	10	Introduced	Y	Other (Class 6)

Poa pratensis is also imported as a crop seed in Canada, *Chenopodium album* should be considered the most widespread general weed. *Echinochloa crus-galli* ranked second among general weeds, detected in seed lots of 17 different crop species. Most of the contaminants found in the highest number of crop species are introduced species, with the exceptions of *Elymus trachycaulus*, *Festuca rubra*, *Galium aparine*, and *Poa pratensis*, which are native. *Bromus tectorum* and *Galium aparine*, both classified as Class 3 noxious weeds, were also among the most widely distributed contaminants (Table 5).

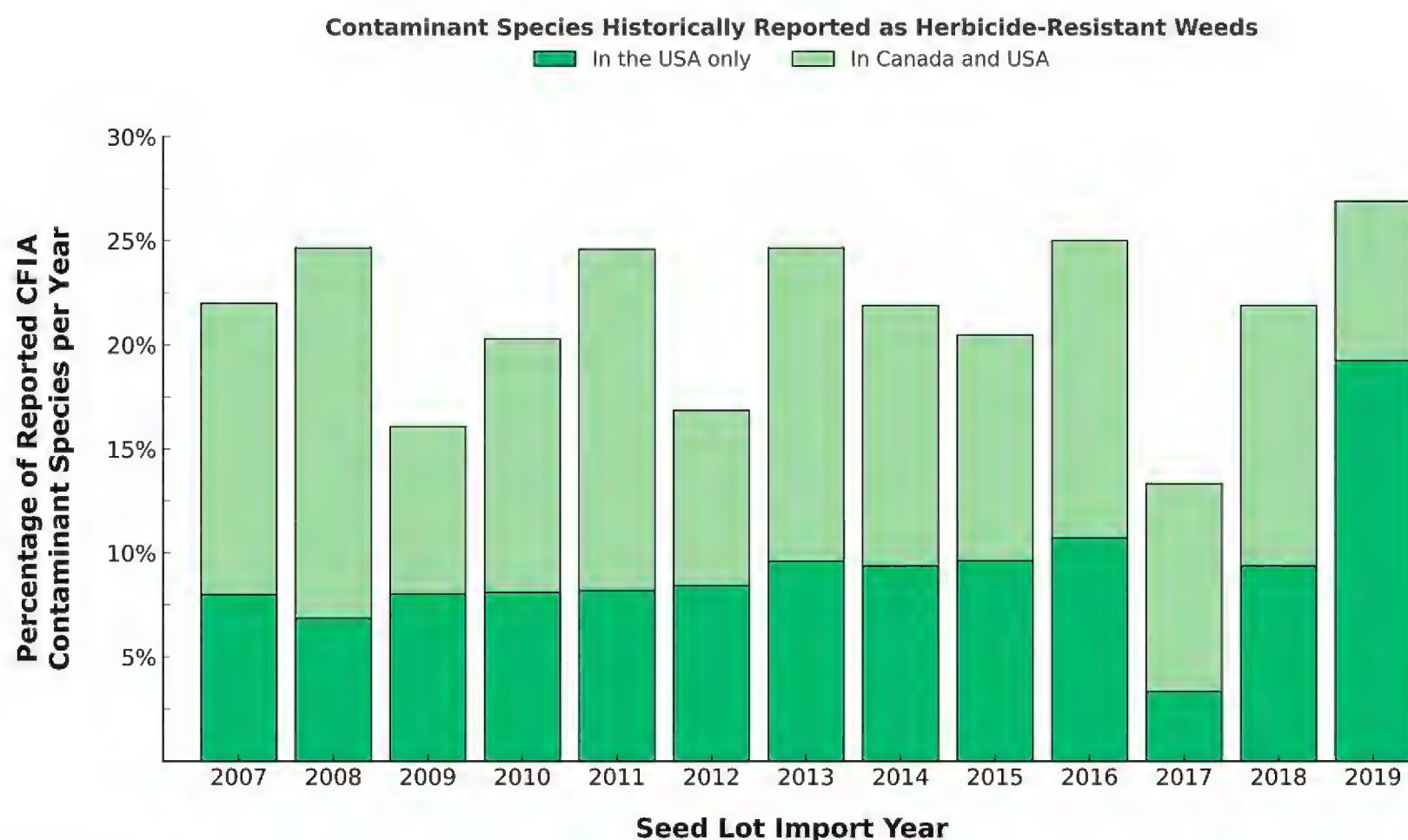


Figure 5. Annual percentage of CFIA-reported contaminant species that correspond to species with a documented history as herbicide-resistant weeds, categorised by whether resistance was previously reported in the USA only or in both the USA and Canada. Note: the y-axis is scaled to a maximum of 30%.

Potential introduction of herbicide-resistant weeds

Fig. 5 shows the percentage of all contaminant species reported in imported seed lots each year that correspond to species historically reported as herbicide-resistant weeds in the USA only or in both the USA and Canada. Although resistance was not confirmed in the seed lots themselves, these species have documented histories as herbicide-resistant weeds in other contexts. On average, 9% of the total contaminant species reported annually were known to be herbicide-resistant weeds in the USA but not in Canada, with a significant increasing trend over time (Mann–Kendall, $\text{Tau} = 0.606$, $p = 0.004$). Additionally, an average of 12% of contaminant species reported each year were known to be herbicide-resistant weeds in both countries, although no significant temporal trend was observed for this group (Mann–Kendall, $\text{Tau} = -0.271$, $p = 0.199$).

Overall, 15 contaminant species reported in Canadian seed lots are known to be herbicide-resistant in a weedy context in the USA but are not currently recognised as such in Canada (Fig. 6). In the USA, herbicide resistance in these species is most associated with arable crops, whereas in the Canadian dataset, the same species were predominantly detected in forage and turf crop seed lots. Notably, four of these contaminant species were reported in the same crop type in both countries. These include *Lolium perenne* (reported in turf crops), *Secale cereale* (in arable crops), *Sorghum bicolor* (in forage crops), and *Poa annua*, which was detected in both forage and turf crops.

Discussion

Improved outcomes in weed seed contamination

Overall, noxious weeds (Classes 1 to 5) were reported significantly less frequently (69% less) than non-noxious species (Class 6), and their presence declined over the study period, although not at a statistically significant level. General weeds

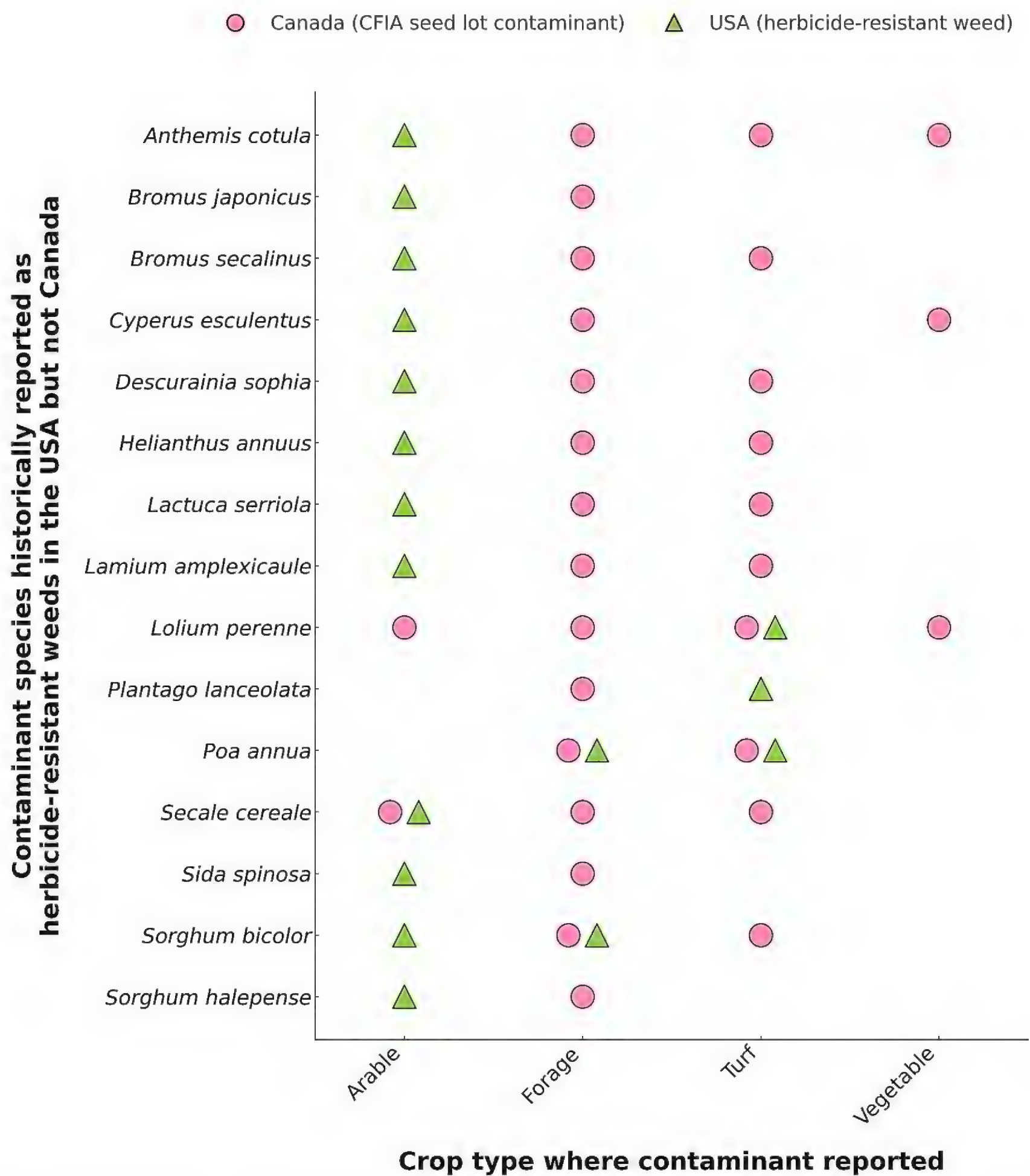


Figure 6. Contaminant species reported as herbicide-resistant weeds in the USA but not in Canada (y-axis), by crop type in which they were reported (x-axis) for each country.

also declined, and in this case, the trend was significant. Additionally, despite the hundreds of unique contaminant species reported in seed lots, the majority were associated with only one or two crop species. All of these findings are encouraging, particularly in the case of noxious weeds, which are associated with greater economic, ecological, and regulatory impacts. These promising trends partly reflect ongoing regulatory oversight and effective industry standards, including the combined influence of herbicide availability, seed certification protocols, advanced cleaning technologies, and improved crop management practices (Rubenstein et al. 2023).

Another encouraging outcome was the low number of reports involving entry-prohibited noxious weeds (Class 1), with only four records, all from a single genus, *Cuscuta*. This rarity is consistent with other international findings. For

example, Rubenstein et al. (2021) analysed over 42,000 seed lots entering New Zealand from more than 90 countries and found entry-prohibited weeds in just 0.06% of cases. Reflecting similar priorities, New Zealand's Ministry for Primary Industries also classifies the entire *Cuscuta* genus as entry-prohibited in seed lots (MPI 2025), and their domestic seed industry includes *Cuscuta* spp. on a list of 14 'undesirable weeds' (Young 1984). The presence of these species in a domestic seed lot in New Zealand can prevent it from achieving seed certification and substantially reduce its market value, providing a strong incentive for industry compliance. The economic, ecological, and health risks associated with such species help explain why both regulators and seed producers consistently prioritise their exclusion, whether in Canada, New Zealand, or other seed-importing nations.

Primary noxious weeds (Class 2), although not entry-prohibited, were more frequently reported. The most commonly reported were *Cirsium arvense* and *Elymus repens* (each in 9 seed lots), followed by *Convolvulus arvensis* (7). These species are already present in Canada but have not reached their full ecological range and are not subject to official control (CFIA 2011). Additionally, Class 2 weeds can lower seed value, interfere with agricultural production, and pose broader economic and environmental risks. Their repeated detection in imported seed lots underscores the need for continued monitoring.

Regulatory complexities: native species classified as entry-prohibited

The emphasis on excluding specific weeds becomes more complex when the species in question is both entry-prohibited and native to the importing country. This was the case for *Cuscuta campestris*, a Class 1 weed reported in the CFIA dataset that is native to Canada and already established in all the southern provinces except New Brunswick (Desmet and Brouillet 2013). Other native species reported as noxious weeds in seed lots included *Ambrosia artemisiifolia* (Class 3), *Galium aparine* (Class 3), *Panicum capillare* (Class 4 or 5), and *Panicum virgatum* (Class 4 or 5). While these species are not prohibited in seed lots, their presence is regulated. This dual classification, especially in the case of prohibited but also native species, can present regulatory challenges. Federal agencies oversee seed imports, while provinces manage established weeds, and this division of responsibilities may lead to enforcement complications and confusion for industry, particularly when a prohibited species is already widespread in some regions of the country but not others.

Regulatory overlap: crops also classified as noxious weeds

Additional regulatory complications arise when species that are noxious or otherwise problematic weeds are imported intentionally as crop seed. While Class 1 noxious weeds are prohibited from entering Canada, species from other noxious classes may still enter, either as seed lot contaminants or, in some cases, as imported crops. Although relatively uncommon in the CFIA dataset, this occurred for *Bromus tectorum* (Class 3), as well as *Panicum miliaceum* (Class 4 or 5) and *Panicum virgatum* (Class 4 or 5). Of these, only *P. miliaceum* (proso millet) is formally listed in CFIA documentation of crop species (CFIA 2022, 2024a). The legal importation of such species may pose a risk to more local weed control efforts if these plants establish and spread.

Bromus tectorum (downy brome) is of particular concern, as it was identified as one of the most widely distributed contaminant species across multiple crops. It is

already recognised as problematic due to its rapid spread and persistence as a winter annual in western North America. It disrupts cropping systems, degrades pasturelands, and readily establishes in both naturalised and disturbed habitats (Geddes and Pittman 2022). Despite these impacts, the CFIA notes that *B. tectorum* ‘has a dual role as a serious weed and an important forage’ crop (CFIA 2017b). However, it remains one of the most problematic weeds in crops like winter wheat, where it competes aggressively with the crop and can cause substantial yield losses if left unmanaged (Ostlie and Howatt 2013). It is also considered one of the most troublesome herbicide-resistant weeds in parts of the USA, particularly in the Great Plains (Brunharo et al. 2022). While herbicide-resistant populations have been reported in both forage and arable systems in the USA since the mid-1990s (Heap 2025), resistant biotypes were not detected in Canada until 2021, when they appeared in a canola field (Geddes and Pittman 2022). This underscores the need for heightened attention to its potential long-term impact on Canadian agriculture.

Cases like these illustrate a broader challenge faced by biosecurity systems, including in Canada, where the same species can be legally imported as crop seed while being managed as a problematic weed at the provincial level. The CFIA, as the federal body responsible for seed import regulation, applies the Weed Seeds Order to determine permissible species and thresholds. However, the responsibility for managing weed impacts post-entry often falls to provincial governments and producers, who may be trying to suppress the very species arriving legally through imports. Without strong coordination between import policies and domestic weed control strategies, high-risk species may establish, complicating eradication or containment efforts once they are widespread.

A similar situation exists with *Poa annua* (annual bluegrass), which is not classified as a noxious weed in Canada but is currently designated as a crop in CFIA documentation (CFIA 2022, 2024a). Despite its crop designation, *P. annua* has been regarded as a problematic weed in temperate regions worldwide, including Canada (Warwick 1979; Hutchinson and Seymour 1982). It is particularly difficult to control in turfgrass and forage systems due to widespread herbicide resistance, including glyphosate resistance (Heap and Duke 2018). Herbicide-resistant *P. annua* has been reported in twelve countries across four continents, including the USA, although no resistant populations have yet been recorded in Canada (Heap 2025). In the CFIA dataset, *P. annua* was one of the most frequently reported contaminants, appearing in seed lots of 13 different crop species. Although it was not imported as a crop during the thirteen-year study period, its frequent occurrence as a contaminant, wide distribution across Canada, resistance history abroad, and status as a problematic weed in multiple trading partner countries suggest its current crop status may warrant reassessment (Desmet and Brouillet 2013; Rubenstein et al. 2023).

Biosecurity considerations for absent species

Beyond the regulatory classification of noxious weeds, the origin status of contaminant species offers a valuable lens for assessing biosecurity risks. Although introduced species were the most frequently reported origin type, absent species (those not currently present in Canada) warrant particular attention. Their detection in seed lots indicates a potential pathway for new plant introductions. If these species establish after sowing, they may become invasive, particularly in Canadian regions

with climates similar to those where the species are already established. This risk is heightened for species with traits associated with invasiveness or the ability to contaminate a broad range of crop types.

Regulatory complexities: absent species permitted in seed lots

Among the general weeds not yet present in Canada, all were classified as Class 6 under the Weed Seeds Order (WSO), a category that excludes noxious weeds. This class includes both common weeds already widespread in Canada, such as *Chenopodium album*, and species not yet recorded in the country, many of which have not been formally assessed for biosecurity risk. However, three of the absent general weeds, *Bromus catharticus*, *Euphorbia aleppica*, and *Trifolium vesiculosum*, are listed in preliminary weed risk analysis documents recently published by CFIA (CFIA 2025b). These species were selected for early assessment due to their potential phytosanitary concern and have undergone the first stage of risk analysis, although no formal regulatory decisions have been finalised. The assessment suggests that *Bromus catharticus* (rescue grass) poses an environmental threat, while *Euphorbia aleppica* (Aleppo spurge) may present a risk to agriculture.

Regardless of their status, all Class 6 species are permissible in seed lots, provided their presence remains below the allowable threshold for the relevant crop type and seed grade (CFIA 2016b). This provision may reflect a regulatory gap, as absent species with the potential to establish and spread could present a higher biosecurity risk than widespread, low-impact species, yet both are treated equivalently under current rules.

To address this security risk, the CFIA could consider introducing a separate classification for absent species detected in imported seed lots, under which a seed lot could be temporarily restricted until the species is identified and a preliminary risk triage is completed. This would not require a full pest risk assessment prior to release but could instead rely on a rapid screening protocol used in weed risk assessment frameworks (Downey et al. 2010), which would evaluate key factors such as the species' global distribution, known invasiveness, and potential climatic suitability in Canada. Where initial risk appears low, the seed lot could either be released as is or conditionally released with post-entry monitoring. Where risk is potentially high, the seed lot could be held pending further assessment, re-cleaned, or returned to the exporter. These approaches would help balance trade continuity with Canada's biosecurity objectives.

Currently, of the CFIA noxious weed classes, only species classified as Class 1 noxious weeds are explicitly prohibited from entering Canada in a seed lot. Although this class includes some species not yet present in Canada, it remains limited in scope, comprising just 25 species and one genus (*Cuscuta* spp.), and has not been updated since the most recent revision of the WSO in 2016 (CFIA 2016b). Adding or removing species from this list requires a formal regulatory amendment following stakeholder consultation, a process that can take several years; the previous update occurred in 2005. The "Plant Protection Act" authorises the CFIA to prevent the importation and spread of harmful plant pests and may offer a more responsive mechanism than the WSO for addressing emerging biosecurity threats. However, it appears to have been used infrequently to regulate weeds, with only five plant species publicly documented as added since 2008 (CFIA 1990, 2024b). In practice, the Act is more commonly applied to insects and plant pathogens. The

most recent publicly documented weed addition occurred in 2017, when *Arundo donax* (giant reed) was added to the list of regulated pests (CFIA 2017a).

A more fluid framework for updating Canada's list of entry-prohibited species may be warranted to better address concerns related to novel or absent species with the potential to establish. New Zealand presents a relevant example, with its Ministry for Primary Industries maintaining a quarantine weed list of more than 1,700 species prohibited from entry (MPI 2022). This list is supported by their "Emerging Risks System", which allows for real-time updates informed by new scientific literature, international biosecurity alerts, and submissions from industry and the public (Bockstruck 2025). While New Zealand's smaller regulatory scale and lower volume of seed imports may make such a system easier to implement, elements of this approach could help inform improvements to Canada's framework.

Most common absent species: *Trifolium vesiculosum*

A notable example of an absent species that may warrant closer attention is *Trifolium vesiculosum* (arrowleaf clover), the most frequently reported absent species in the dataset and native to the Mediterranean. It was detected in forage crop seed lots of *Trifolium pratense* (red clover) and *Trifolium repens* (white clover). This contamination pattern aligns with previous findings showing that clover crops are often contaminated by other *Trifolium* species (Rubenstein et al. 2021). Such contamination is facilitated by the morphological similarity between the crop and contaminant, which complicates mechanical cleaning and limits herbicide options, as chemistry targeting the weed would also damage the crop (Rubenstein et al. 2023). While *T. vesiculosum* is not currently cultivated in Canada, it is widely used in pasture and cover crop seed mixtures in warmer regions of the USA (Pemberton et al. 1998). Although not typically considered invasive, the CFIA recently identified *T. vesiculosum* as a potential phytosanitary risk in a preliminary weed risk analysis (CFIA 2025b). Its repeated detection in seed lots, along with other frequently reported absent species, raises concerns about potential establishment, particularly given its ongoing cultivation in a neighbouring country and the possibility that climate change could expand its suitable habitat in Canada.

Climatic overlap and establishment potential of absent species

This risk of establishment is particularly relevant in regions where Canadian and USA climates overlap. Several other reported contaminant species classified as absent from Canada are already established in nearby USA regions. For example, *Trifolium hirtum* (rose clover) is a well-established introduced weed in northern California and is considered invasive in parts of its introduced range (iNaturalist 2025c). *Torilis nodosa* (knotted hedge-parsley) and *Galium parisiense* (wall bed-straw) are both widespread introduced weeds in the Pacific Northwest and eastern USA (iNaturalist 2025a, 2025b). Their presence in climatically similar areas underscores the potential for establishment in Canadian provinces such as British Columbia, a key region for crop seed production.

While absent species reported as seed lot contaminants raise biosecurity concerns, their classification alone does not always imply high establishment risk. Many may be poorly suited to Canadian conditions, such as regions with long winters, or may be associated with crop types rarely grown domestically (Wilson et

al. 2016). Still, documenting these species in imported seed lots remains important for biosecurity monitoring and should be considered alongside other risk factors, including climatic suitability and detection frequency.

Introduced species with the potential to spread

In addition to absent species, eight contaminant species were recorded as introduced, but only in a single Canadian province. These species may present even greater concern, as they have already demonstrated an ability to establish under Canadian conditions. It is likely that similar climates in neighbouring provinces could support their spread, potentially resulting in broader ecological and economic consequences. The most frequently reported among these eight species was *Apera spica-venti* (silky bentgrass), a grass weed introduced in Ontario (Desmet and Brouillet 2013). It was reported in 28 seed lots of *Poa pratensis* (Kentucky bluegrass), two lots of *Poa trivialis* (rough bluegrass), and one lot of *Agrostis gigantea* (redtop). Its repeated appearance in grass seed lots suggests a consistent introduction pathway and underscores the need for closer regulatory scrutiny. As with *Trifolium* species discussed prior, grass contaminants such as *Apera spica-venti* are difficult to remove mechanically from grass seed due to their similar morphology, and selective herbicide options are limited, as treatments that target grass weeds often also damage the crop. Although not currently herbicide-resistant in Canada, *A. spica-venti* has evolved resistance in more than eleven European countries, most of which export seed to Canada (Heap 2025). Its resistance spans multiple modes of action, making it challenging and costly to manage once established. It has also been identified as a high-risk candidate for future resistance in New Zealand, where it is frequently reported in seed lots (Hulme 2024). Given that New Zealand's temperate cropping systems and agronomic practices resemble those in Canada, its experience offers a cautionary example of the risks of establishment and resistance.

Sorghum halepense (Johnson grass) is another case of concern. It has only been reported in one Canadian province, Ontario (Desmet and Brouillet 2013), and in the CFIA data was reported in seed lots of *Sorghum × drummondii* (Sudan grass). Classified as a Class 2 – Primary noxious weed, it is not yet considered to be occupying its full ecological range in Canada (CFIA 2011). Globally, *S. halepense* is recognised as one of the world's worst weeds, ranking among the ten most troublesome species (Holm et al. 1997). It has evolved herbicide resistance in over a dozen countries, including the USA, though no resistant populations have yet been confirmed in Canada (Heap 2025). An aggressive perennial that spreads by both seed and rhizomes, it is notoriously difficult to control once established. Its detection in seed imports highlights the importance of early identification and targeted regulatory action to prevent further spread.

Most widespread general weed: *Chenopodium album*

While the majority of contaminant species were detected in only one or two crop species, some weeds appeared across a broader range. Most notably, *Chenopodium album* (common lamb's quarters), an introduced species in Canada, was reported in seed lots of 22 different crop species, making it the most widespread general weed in the dataset. This is concerning given its global reputation as a persistent and herbicide-resistant weed in seed production systems (Hulme 2024). Rubenstein

et al. (2021) found *C. album* to be the most frequently reported contaminant in an analysis of over 42,000 seed lots representing 1,400 crop species imported into New Zealand. Similar patterns have been observed elsewhere: it was the most common weed in *Trifolium pratense* (red clover) seed lots imported into India (Singh et al. 2010) and in grain seed shipments entering Japan (Ikeda et al. 2022). Its widespread persistence is likely due to its ecological adaptability and ability to evade post-emergence herbicide applications by germinating later in the crop cycle, allowing even late-emerging individuals to mature and produce seed (Williams 1963; Rubenstein et al. 2021). In Canada, *C. album* is already recognised as herbicide-resistant in five provinces, and globally it has evolved resistance in 20 other countries, including multiple cases in the USA (Heap 2025). Although already widespread, continued monitoring is important to detect the introduction of resistant biotypes into provinces where resistance has not yet been recorded.

Emerging herbicide-resistant weed risks from imported seed

On average, 9% of the contaminant species (15 species) reported each year were known to be herbicide-resistant weeds in the USA but had not yet been reported as such in Canada. This proportion increased significantly over the study period. These findings suggest a growing risk of new herbicide-resistant weed biotypes being introduced into Canada via the imported crop seed pathway. Several contaminant species highlighted earlier in this discussion fall into this category, including *Sorghum halepense* and *Poa annua*, which are not currently recognised as HR weeds in Canada but are in the USA (Heap 2025).

Of particular concern are four species that were detected as contaminants in the same crop types in both Canada and the USA. For example, *Poa annua* was found in forage and turf seed lots entering Canada, and it has also previously been reported as HR in a weedy context in those same crop types in the USA (Heap 2025). Similar patterns were observed for *Lolium perenne*, *Secale cereale*, and *Sorghum bicolor*, all of which were reported as Canadian seed lot contaminants in turf, arable, and forage crops, respectively. All have also been documented as herbicide-resistant weeds in the same crop types in the USA (Heap 2025). The biosecurity risk is heightened by the fact that some of these species are also cultivated as crops in both countries, increasing the likelihood that resistant biotypes could establish and spread. These cases illustrate a clear pathway for the introduction of resistant weeds into Canadian agroecosystems.

Factors influencing herbicide resistance patterns

Several factors discussed by Brunharo et al. (2022) help explain why certain weed species are herbicide-resistant (HR) in the USA but not in Canada. In the USA, widespread adoption of glyphosate-resistant (GR) crops, particularly soybean, maize, and cotton, has led to simplified weed control programmes that rely on a single or limited number of herbicide sites of action (SOAs). This has placed strong selection pressure on weed populations, contributing to the evolution and spread of GR weeds. In contrast, Canadian cropping systems more often include a broader diversity of HR traits and crop types, which likely contributes to the slower development of resistance. Brunharo et al. (2022) also note that more diverse crop rotations, common in the Canadian Prairies, incorporate a wider range of

crops and herbicide SOAs and have been associated with lower GR weed pressure. By comparison, simplified maize–soybean rotations are common in the USA and linked to higher HR weed frequencies. These contrasting patterns highlight the importance of rotational and herbicide diversity in managing resistance. Other contributing factors may include differences in climate, specific herbicides used, and national approaches to resistance monitoring and reporting.

Herbicide-resistant species with potential for further domestic spread

In addition, an average of 12% of contaminant species reported annually in the CFIA dataset were already herbicide-resistant weeds in both the USA and at least one Canadian province. Given the wide geographic distribution of these species in North America and their current presence in Canada, their continued detection in imported seed lots increases the risk of resistance traits spreading to additional Canadian provinces. This group includes several problematic weeds, such as *Echinochloa crus-galli* and *Bromus tectorum*, which have both only been reported as herbicide-resistant weeds in Ontario (Guo et al. 2017; Heap 2025).

Another notable example is *Setaria viridis*, which was among the most widespread general weeds in imported seed lots, reported in ten different crop species. Its inclusion is worth mentioning, as *S. viridis* ranks as the third most frequently reported herbicide-resistant weed species in Canada, and resistant biotypes have already been detected in four provinces (Heap 2025).

Seed characteristics influencing seed lot contamination

Understanding how seed characteristics influence seed lot contamination helps clarify broader patterns across crop types. The absence of a significant correlation between inspection frequency and contamination rates (Spearman's correlation, $p = 0.560$) suggests that factors aside from frequency of inspection play a more important role. For example, although *Zea mays* (maize) was the most frequently inspected crop, it had the lowest contamination rate. In part, this low rate of contamination is related to the efficiency of cleaning large-seeded arable crops like *Z. mays*, where pronounced differences in size and weight make weed seeds easier to remove (Wych 1988; Wilson et al. 2016; Gervilla et al. 2019). In contrast, smaller-seeded forage and turf crops are more difficult to clean and tend to show higher contamination rates (Rubenstein et al. 2021; Buddenhagen et al. 2022). In the CFIA dataset, *Trifolium repens* (white clover), a forage crop, had the highest contamination rate among frequently inspected species. These results are consistent with findings from New Zealand, where imported seed lots of *Trifolium* species were among the most frequently contaminated, while large-seeded crops like *Z. mays* had the lowest rates (Rubenstein et al. 2021).

Emerging technologies for seed lot inspection

Advances in biosecurity technology are beginning to address some of the limitations of traditional inspection by providing tools that reduce financial and labour demands while enabling broader, more efficient surveillance. For example, machine learning combined with automated imaging systems can rapidly and consistently identify weed seeds based on external traits such as colour, reflectance patterns,

shape, size, and texture. Recently, the CFIA tested deep learning models using RGB and multispectral imaging for seed lot purity analysis and reported up to 95% accuracy in identifying common weed seeds (Wang 2025). These results demonstrate the practical viability of such systems in regulatory settings, particularly as training datasets expand to include new species, improving model performance over time.

Technologies such as 3D X-ray computed tomography offer an additional advance by capturing both external and internal seed morphology, rather than relying solely on surface traits. High-resolution 3D imagery can be used to train artificial intelligence models capable of distinguishing crop and contaminant seeds based on shape, density, biomass, and internal structure, all within a closed container. Because X-ray scanning is non-invasive, seed samples can be processed in sealed containers within minutes and returned to the lot, reducing reliance on manual inspection (Wolff 2025).

Additionally, DNA barcoding and other molecular diagnostic tools provide another layer of precision, enabling species-level identification even when external traits are ambiguous or seeds are physically damaged (James et al. 2014; Letsiou et al. 2024). Together, these technological advances could provide a scalable means of strengthening seed lot biosecurity as they become more accessible and affordable, while reducing burdens on shippers and regulatory agencies.

Conclusion

Promising biosecurity trends identified in this study included a significant decline in general weeds, a decline in noxious weeds over time, a significantly lower frequency of noxious weeds relative to non-noxious species, the rare occurrence of entry-prohibited species, and the fact that most contaminants were associated with only one or two crop species. Collectively, these outcomes suggest that regulatory oversight and broader industry practices have been effective. However, concerns remain. These include contaminant species not yet recorded in Canada that are either frequently reported (e.g., *Trifolium vesiculosum*), have been classified as threats to agriculture or the environment (*Bromus catharticus*, *Euphorbia aleppica*), or exhibit climatic overlap with regions of the USA (*Galium parisiense*, *Torilis nodosa*, *Trifolium hirtum*). Also of concern are introduced species with limited but potentially expanding distributions (*Apera spica-venti*), generalist weeds that affect a broad range of crop species (*Chenopodium album*), and frequently reported Class 2 – Primary noxious weeds (*Cirsium arvense*, *Convolvulus arvensis*, *Elymus repens*), which have yet to reach their full ecological range in Canada. A further concern is the increase in emerging herbicide-resistant species that may introduce new resistance traits into Canada via the crop seed trade pathway (*Sorghum halepense*, *Poa annua*), as well as species currently recorded as resistant in only one Canadian province, indicating potential for wider spread (*Bromus tectorum*, *Echinochloa crus-galli*). Another concern is the introduction of herbicide resistance through contaminant species present in the same crop types in Canada, where resistant populations are already documented in the USA (*Poa annua* in forage and turf crops).

Additional regulatory concerns that may warrant further attention by the CFIA include the importation of crop species also listed as noxious or problematic weeds (*Bromus tectorum*, *Poa annua*), the allowance of contaminant species not yet recorded in Canada, which are currently classified as Class 6 (non-noxious), and the dual classification of native species as entry-prohibited weeds (*Cuscuta campestris*).

It is worth noting that our conclusions are based on the presence or absence of contaminant species in a seed lot, not the number of weed seeds, as this information was not provided to us. Nonetheless, access to seed count data would be valuable for future research aimed at assessing propagule pressure more directly (Rubenstein et al. 2021; Rubenstein et al. 2023). Although it was beyond the scope of this study, such data, combined with information on a species' climatic suitability and its known invasiveness elsewhere, could support more targeted weed risk assessments.

Our analysis excluded contaminants identified only at the genus or family level, which accounted for about 30% of records. The remaining species-level identifications represented nearly two-thirds of the sampling data, while broader taxonomic entries were omitted to ensure accurate classification. Species-level identification was essential to determine a contaminant's noxious weed class (if applicable), whether it was a general weed, and its origin status. These attributes could not be reliably assessed without species-level resolution. Given these limitations, we encourage reporting contaminants at the highest taxonomic resolution feasible to improve the accuracy and utility of future risk assessments. However, we recognise that species-level identification is often difficult due to incomplete or ambiguous morphological features (James et al. 2014).

Canada's approach of randomly sampling a proportion of all incoming seed lots aims to ensure compliance with import standards and maintain the overall quality of imported seed. In practice, these monitoring activities serve as a form of quality control. In contrast, New Zealand inspects every seed lot at the border, regardless of information provided on the seed analysis certificate for the seed lot, reflecting a more risk-averse approach to biosecurity (Rubenstein et al. 2021). However, for a country the size of Canada, which receives a high volume of seed imports, particularly from the USA, with which it shares a long land border, inspecting every lot is not feasible due to the labour required and the cost of inspection, nor is it necessarily warranted.

Given these practical constraints, several important questions arise. If inspecting every seed lot is not feasible, what proportion should be sampled to ensure compliance? Can the presence of a monitoring system alone deter non-compliance by signalling to exporters that Canada enforces its standards? And if resources are limited, should inspection efforts prioritise imported crops historically associated with entry-prohibited weeds, species absent from Canada, or herbicide-resistant weeds, or some combination of these? For example, our analysis showed that larger-seeded arable crops such as *Zea mays* had the lowest contamination rates, while smaller-seeded forage and turf crops such as *Trifolium repens* had the highest. In weighing all these considerations, it is important to strike a balance between reducing the risk of introducing weeds and avoiding unnecessary barriers to international seed trade.

The factors analysed in this study provide a practical foundation for identifying biosecurity risks, supporting CFIA surveillance priorities, and offering a model for other countries to collect and analyse their own seed import data. We highlight key trends, high-risk contaminant species, and regulatory approaches that may warrant closer scrutiny. At the same time, we acknowledge that policymakers must weigh conservation goals, trade obligations, and agricultural productivity within existing regulatory frameworks. As global crop seed trade continues to grow, sustained monitoring of this pathway will be critical to safeguarding domestic agriculture and natural ecosystems.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Data availability

Information on all reported contaminant species is provided in the figures, tables, and supporting information of this paper.

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Supplementary material 1

Contaminant plant species detected in seed lots imported into Canada from the USA (2007–2019)

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Data type: pdf

Explanation note: Alphabetical list of all contaminant plant species reported by the CFIA in seed lots imported into Canada from the USA between 2007 and 2019. ‘HR’ indicates whether the species has previously been reported as an herbicide-resistant weed in Canada or the USA.

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